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Predictive air-conditioner control for electric buses with passenger amount variation forecast☆

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HIGHLIGHTS

- Monte Carlo, RBF-NN and Markov-chain are employed for the future passenger amount forecast on a bus.
- A model predictive control based air-conditioning system energy management strategy is established for electric buses.
- A comprehensive comparison is performed in terms of cabin temperature, energy consumption and computation.

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ABSTRACT

Air-conditioners (AC) usually consume the most electricity among all of the auxiliary components in an electric bus, over 30% of the battery power at maximum. On-board passengers carried by the electric bus are important but random heat sources, which are obsessional disturbances for the cabin temperature control and energy management of the AC system. This paper aims to improve the AC energy efficiency via passenger amount variation analysis and forecast in a model predictive control (MPC) framework. Three forecasting approaches are proposed to realize the passenger amount variation prediction in real-time, namely, stochastic prediction based on Monte Carlo, radial basis function neural network (RBF-NN) prediction, and Markov-chain prediction. A sample passenger number database along a typical bus line in Beijing is built for passenger variation pattern analysis and forecast. A comparative study of the above three prediction approaches with different prediction lengths (bus stops in this case) is conducted, from both the energy consumption and temperature control perspectives. A predictive AC controller is developed, and evaluated by comparing with Dynamic Programming (DP) and a commonly used rule-based control strategy. Simulation results show that all the three forecasting methods integrated within the MPC framework are able to achieve more stable temperature performance. The energy consumptions of MPC with Markov-chain prediction, RBF-NN forecast and Monte Carlo prediction are 6.01%, 5.88% and 5.81% lower than rule-based control, respectively, on the Beijing bus route studied in this paper.

1. Introduction

1.1. Background

The energy management of the AC system is crucial to maintain the temperature comfort of the passengers in the compartment, especially for electric buses [1,2]. Electric buses have been deployed all across the world and they usually have larger cabins and much more passengers. The large number of passengers could produce plenty of heat within the bus cabin. The variation of the passenger amount is random and fierce on an electric bus, and therefore becomes an obsessional disturbance for the temperature control of the AC system.

What is more, the AC system as an important auxiliary part of the electric bus significantly affects the energy consumption and the driving range of the vehicle. It is usually the largest energy consumption component except the power system, and requires a considerable percentage of the battery energy [3–5]. Considering the range anxiety which electric buses are facing right now, this paper intends to develop passenger amount forecasting methods for predictive energy management of the AC system on an electric bus, and to further improve the vehicle energy efficiency in cooling operation.

In the literature, the energy management of the AC system has been

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Nomenclature

ρ_{air}	the air density
V_{air}	the volume of the cabin air
Q_{driver}	the driver heat dissipation
λ	volumetric efficiency
n	compressor rotation speed
n_p	the number of passengers
n'	the clustering coefficient
J_1	the energy consumption
h	nonlinear activation function
c	the neural net center
ω	the weight of output layer
$time$	the time of day
T_s	the preset temperature
Q	the total heat loads
V	the compressor displacement
I	solar radiation intensity
γ	the latent heat of vaporization
C_{Pair}	the heat capacity of indoor air
J_2	measuring the cabin comfort
x	the input parameter
y	the output of the neural network
b	the spread width
$N_{history}$	the historical number of passengers
W	the power
F_{fg}	the effective area of the windows in direct sunlight
ρ_s	the absorption coefficient of solar irradiance through the body
T_{ots}	the integrated temperature outside caused by solar radiation, $T_{ots} = T_o + \rho_s I/\alpha_O$
ω_1,ω_2	the weight coefficients which determine the importance of J_1 and J_2 respectively
C_V	specific volume when the refrigerant is in the suction process
Q_{body}	the convective heat flows between the indoor air and the body surfaces
Q_{grass}	the convective heat flows between the indoor air and the windows
$Q_{sun},Q_{passengers},Q_{others}$	load by incident solar radiation, passengers, the electrical auxiliaries
Q_{top}, Q_{floor}, Q_{side}	the convective heat from the roof, the floor and the body side
K_t, K_f, K_s	the heat transfer coefficient of the roof, the floor and the body side
$F_t,F_f,F_s,F_{gf},F_{gr},F_{gs}$	the area of the roof, the floor, the body side, the front windshield, rear window, side windows
T_o,T_i,T_{ot}	the outdoor air temperature, the indoor air temperature, the roof temperature
Q_{gfront}, Q_{grear}, Q_{gside}	the convective heat from the front windshield, rear window and side windows
K_{gf},K_{gr},K_{gs}	the heat transfer coefficient of the front windshield, rear window and side windows
η	the penetration coefficient of solar irradiance through the windows
$a_{history}$	the historical rate of change in the number of passengers
$weather$	the weather information, such as rain, snow, fog and so on

widely studied [6–12]. Khayyam et al. proposed fuzzy control to manage the operation of the air conditioning system, the evaporator, the blower, fresh-air and the recirculation gates to achieve desired comfort temperature and indoor air quality while minimizing energy consumption under various environment conditions and different road load conditions via a look-ahead system [6–9]. Huang et al. presented an intelligent model predictive controller and sliding mode controller for the automotive air-conditioning or refrigeration systems, with the energy consumption greatly saved [10–12]. A detailed system-level approach to reduce the heating, ventilation and air conditioning (HVAC) energy consumption of electric vehicles was developed as a function of transient environmental parameters including local ambient temperature, local solar radiation, local humidity, duration and thermal soak in [13,14]. The resulting engineering toolset is used to study the influence of environmental factors on the driving range and to determine the summation and geographical distribution of energy consumption by HVAC systems in electric vehicles.

Besides, a low-order, energy-based model of an automotive AC system was proposed in [15], and is able to predict the dynamics of the evaporator, the condenser pressures and the compressor power consumption during typical thermostatic operations. An optimal control problem of an advanced AC system with a storage evaporator was described in [16] which enables the ability to balance fuel consumption, cabin comfort and drivability constraints. A mathematical model and a control system were developed to study the effect of the AC systems on vehicles in [17]. MPC has been proved to be a powerful tool to control the HVAC systems in a real-world test system, which illustrated the effectiveness of MPC control effect in practical applications [18].

The above studies achieved certain energy-saving performances from different aspects. However, to the author's best knowledge, the study on forecasting passenger numbers for predictive control of the AC system in an electric bus is still lack in the literature.

1.2. Innovation

Random and fierce changes in the number of passengers (e.g. boarding on and getting off) directly increases the cooling power of the AC system for an electric bus and affects its driving range, especially on workdays. Being aware of the passenger number information in the future bus stops is of great significance for the energy optimization and power control of the AC system. It is able to foresee the future heat load of the cabin and adjust the control sequence in time which can provide the controller a better ability to improve the energy economy performance of the AC system.

This paper aims at evaluating the role of passenger number forecasting in the predictive energy management of an electric bus based on model predictive control. Three different passenger amount forecasting approaches are proposed and investigated, namely stochastic prediction based on Monte Carlo, RBF-NN prediction and Markov-chain prediction. The above three methods are systematically compared in terms of cabin temperature control and energy efficiency performances. DP is used to solve the power behavior optimization problem of the AC system during each control horizon in the proposed MPC framework. This study eventually provides better understanding of predictive energy management of the AC system in electric buses, and the passenger amount forecasting's influence on bus range improvement.

1.3. Organization

The remainder of this paper is organized as follows. In Section 2, the modelling of the AC system and the real-life bus passengers' number database collection are introduced. Three types of passenger amount variation prediction methods are described in Section 3. A nonlinear MPC energy management strategy is presented in Section 4, including the application to the AC system. Section 5 draws the simulation results and discussions, with the main conclusions summarized in Section 6.